Measurement of liquid complex dielectric constants using non-contact sensors

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Abstract—Our primary objective in this work is the accurate measurement of complex dielectric constant and conductivity of unknown liquids. In this paper we present design, fabrication, and testing results for an IDC (interdigitated capacitor) electrode sensor for use as a fluid monitoring component that can be integrated into a microfluidic system. Unlike prior work we show how to accurately extract both the conductivity and permittivity of liquids, for loss tangents ranging from much less than one to greater than one (i.e., from lossy dielectrics to conductors); this has not been shown in previous work. In addition, we also demonstrate a method of remotely accessing the IDC sensor by wireless inductive coupling similar to EAS (Electronic Article Surveillance) tags.

I. INTRODUCTION

The miniaturization of chemical and biological sensors has received considerable attention in recent years for medical diagnostics, environmental monitoring, pharmaceutical screening, military applications, etc. One interesting area of development in microfluidic systems is detecting dielectric properties of a MUT (Material Under Test) using IDC electrodes (Fig. 1). IDC-based chemical sensors have been investigated by many researchers because they are cheap to manufacture and can be easily integrated with other sensing components and signal processing electronics. Unfortunately the methods discussed previously for extraction of dielectric constant are valid only when the MUT is lossless. In this paper we present a data extraction method and experimental results for materials ranging from essentially lossless (e.g., air, isopropyl alcohol, oil, etc.) to very lossy (e.g., salt water and nano-wire suspensions).

II. MODELS FOR PARAMETER EXTRACTION

A. Conformal mapping for IDCs

A useful method for the calculation of the capacitance of IDC structures is the conformal mapping technique. Conformal mapping provides closed form expressions for the computation of the capacitance of IDC electrodes based on the geometry and property of the sensor. In 1977 Wei first evaluated the capacitance of an IDC with an infinite top layer based on conformal mapping [1]. This model was extended and improved by Veyres and Hanna [2] to evaluate the capacitance for a sensor having a finite layer structure in 1980. Since then, the model used by Veyres et al. has played an important role in analyzing the IDC structure in a variety of scientific applications. In our lab, Wentworth et al. used the model to characterize tape automated bonding (TAB) interconnect in 1989 [3]. In 1996 Gevorgian et al. [4] proposed a different model for an IDC with a multilayered top structure based on the same conformal mapping technique. The more general form for multilayered IDC electrodes was discussed by Igreja in 2004 [5]. A major limitation of these approaches, however, is their applicability only to lossless layers (i.e., layers with zero conductivity).

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mapping approach [5] if the MUT has a dielectric constant greater than the insulating layer the conformal mapping approach generates a negative capacitance in the equivalent circuit model, as illustrated in Fig. 2. Although this is mathematically correct, it has no physical significance, and when the MUT layer has finite conductivity it is not possible to use this “negative” element in extraction.

\[
\begin{align*}
C_{\text{ins}} &= 2 \varepsilon_e \varepsilon_{\text{a.s.}} \frac{K'(k_1)}{K(k_1)} \\
C_{\text{sub}} &= 2 \varepsilon_e \varepsilon_{\text{a.s.}} \frac{K'(k_2)}{K(k_2)} \\
C_{\text{mut}} &= 2 \varepsilon_e \varepsilon_{\text{a.s.}} \frac{K'(k_3)}{K(k_3)} \\
\end{align*}
\]

Figure 2: Illustration of insulated interdigitated capacitor equivalent circuit model used in normal conformal mapping; \(K\) and \(K'\) are the elliptic integral from the conformal map.

B. New model for extraction

To avoid the problems inherent in the direct conformal mapping approach we adopt a somewhat different equivalent circuit model that is more directly physical, as illustrated by Figs. 3 and 4. There are four primary flux components. The first is entirely contained in the supporting substrate, producing an admittance \(Y_{\text{sub}}\), the real part representing loss and the imaginary part representing the capacitance from the substrate. The next three components are all functions of both the (complex) dielectric constant of the IDC insulating layer and the (complex) dielectric constant of the MUT. One component represents flux entirely contained within the IDC insulating layer (\(G_p\) and \(C_p\)). The next two components are used to represent flux that passes first through the insulating layer (\(G_{\text{ins}}\) and \(C_{\text{ins}}\)) and then “closes” through the MUT (\(G_{\text{MUT}}\) and \(C_{\text{MUT}}\)).

It is not possible to find an exact value of \(C_p\) or \(C_{\text{ins}}\) because both are also dependent on the MUT, however we have found that using an upper bound value for \(C_p\) works well. This value is found by first assuming the MUT is “air” (i.e., \(\varepsilon_{\text{MUT}} = \varepsilon_0\)) and that \(C_{\text{ins}}\) is a simple parallel plate capacitor using the finger width, insulator thickness, and insulator dielectric constant to evaluate \(C_{\text{ins}}\) (see Fig. 5). The value of \(C_{\text{air}}\) is found using conventional conformal mapping assuming an IDC with no insulating layer, while the total capacitance of the insulated IDC with air above the insulator is found using the conventional layered conformal mapping technique. Setting that total capacitance equal to that of the equivalent circuit shown in Fig. 5 with “known” values of \(C_{\text{air}}\) and \(C_{\text{ins}}\) (as discussed above) allows the final calculation of \(C_p\).

Once \(C_p\) has been fixed it is possible to find an analytic form for \(C_{\text{ins}}\) that is a function of both the insulator dielectric constant and the MUT dielectric constant. The equivalent conductance (loss) due to flux within the insulating layer is represented by \(G_{\text{ins}}\). This term can be estimated based on the previous \(C_p\) estimation and the relationship between \(C_{\text{ins}}\) and \(\varepsilon_{\text{mut}}\) using actual measurement data when the MUT is air. Now using this model in an iterative fashion we can self-consistently extract both the real and imaginary parts of the MUT dielectric constant (or equivalently the permittivity and conductivity or loss tangent) from actual measured data; no prior knowledge or estimate for the dielectric constant or conductivity of the MUT is required.

\[
\begin{align*}
\varepsilon' &= \varepsilon - j \frac{\sigma}{\omega} \\
\end{align*}
\]
III. EXPERIMENTAL VERIFICATION

The devices used for actual measurement are formed using evaporated aluminum on a glass substrate covered with a dielectric insulation layer of SU-8 about 15 μm thick, as illustrated in Figure 6. The chips were directly attached to a connector, and swept frequency measurements were made using a HP Gain-Phase Analyzer. In order to test the extraction procedure a number of liquids with known dielectric constant were first measured. Figure 7 shows exemplary results for isopropyl alcohol (IPA). The measured relative dielectric constant was nearly frequency independent and within 7% of the low frequency handbook value for IPA. IPA is expected to be essentially lossless; our measurement-extracted loss tangent of between 0.005 and 0.01 indicates that the procedure used did an excellent job removing “extraneous” losses due to the SU8 and packaging parasitics.

Figure 6: Fabricated IDC device and mounting to allow rf measurements

Figure 7: Extracted ε and loss tangent for IPA.

A much more challenging test is the measurement of a high dielectric constant material such as water. Figure 8 shows the measurement-extracted results for de-ionized (DI) water that are again in excellent agreement with expected values.

Figure 8: Extracted ε and loss tangent for DI H2O.

The most difficult test of the extraction procedure occurs for liquids with a high conductivity, such as salt water. Figure 9 shows the measurements for a salt solution with dc conductivity of 17 mS/cm, again showing that the procedure is quite accurate.

Figure 9: Extracted ε and loss tangent for salt water.

Overall Figs. 7-9 clearly demonstrate that the IDC system and the extraction methodology discussed above can be used to accurately find both the dielectric constant and conductivity of liquids with widely varying characteristics.

IV. NON-CONTACT WIRELESS SENSOR “TAGS”

We have also demonstrated an approach for a non-contact measurement technique in order to detect changes in the dielectric properties of a MUT using a simple magnetically coupled wireless sensor, similar in concept to EAS (Electronic Article Surveillance) tags. These tags consist of a simple inductor-capacitor resonant circuit which is characterized by a specific resonant frequency $f_0$. If the capacitor in the resonant circuit is an IDC then any changes in MUT dielectric constant should evidence themselves as a change in $f_0$, while any changes in MUT conductivity should appear as a change in pseudo-Q [6]. The basic non-contact measurement configuration is illustrated in Fig. 10. The reader coil is inductively coupled to a sensor tag formed by the connection
of a tag coil and an IDC. In this configuration measurements can be made at a distance without direct physical contact with the tag.

![Non-contact inductive pickup equivalent circuit.](image)

Figure 10: Non-contact inductive pickup equivalent circuit.

The characteristics of the resonant tag are most easily seen in the phase response at the input of the reader coil. Figure 11 shows typical results for several test solutions of widely varying dielectric constant and conductivity.

![Non-contact sensor tag phase response for different liquids.](image)

Figure 11: Non-contact sensor tag phase response for different liquids.

V. SUMMARY

In this paper we have shown testing results for an IDC (interdigitated capacitor) electrode sensor for use as a fluid monitoring component that can be integrated into a microfluidic system. Unlike prior work we have shown how to accurately extract both the conductivity and permittivity of liquids, for loss tangents ranging from much less than one to greater than one (i.e., from lossy dielectrics to conductors); this has not been shown in previous work. In addition, we have also demonstrated a method of remotely accessing the IDC sensor by wireless inductive coupling similar to EAS (Electronic Article Surveillance) tags.

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